CALIFORNIA DIVISION OF MINES AND GEOLOGY
FAULT EVALUATION REPORT FER-144

Pond Fault, Northern Kern County

by

Theodore C. Smith
Associate Geologist

April 12, 1983

INTRODUCTION

The Pond fault, located in northern Kern County near the community of Pond, lies in the Pond 7.5-minute quadrangle (see Figure 1). This fault is being evaluated as part of a state-wide effort to evaluate faults for recency of movement. Those faults determined to be sufficiently active and well-defined are zoned by the State Geologist as directed by the Alquist-Priolo Special Studies Zones Act (see Hart, 1980).

SUMMARY OF AVAILABLE DATA

During the investigation of a potential site for a nuclear power plant, evidence of historic fault rupture (creep) was discovered near Pond (Los Angeles Department of Water and Power [LADWP], 1974). The surface evidence consisted of down-dropped roadways, ground cracks and sags, and repeated pipeline ruptures as noted on Figure 2. Subsurface evidence consisted of a groundwater barrier (along Peterson Road the groundwater level in borehole 3 was 50 feet below the surface, and in borehole 8 was 80 to 83 feet below the surface; see Figure 2) and offset stratigraphic horizons (see Figure 3). The latter offset, documented by trenching, amounted to 9" (apparent vertical) at a depth of 10 feet below the surface. LADWP depicts the surficial materials at the trench sites as Modesto Formation (late Pleistocene in age).

In addition to developing the above data, LADWP also analyzed vibration seismic data (both their own original data and older data purchased from other sources). Also, several boreholes were drilled in the area [neither the logs of these boreholes nor the e-logs were in the CDMG copy of the report, however; also missing were the data on vibroseis line GSC-2]. Based on these data they concluded that the Pond fault consists of a 2/3 mile-wide zone of northwesterly trending normal faults, downthrown to the southwest and dipping approximately 50° to 70°. The subsurface data indicate that repeated movement has occurred along this fault zone since Eocene and possibly Paleocene time (LADWP, 1974, p. 2.5E-67A). They concluded that the amount of total displacement along the zone decreased in a northwesterly direction. They also concluded that the westernmost fault detected in vibroseis line GSC-1 has the largest apparent vertical offset, which appears to increase in depth as shown in Table 1. This fault, if projected to the surface based on these data, would be expected to crop out near Lytle Avenue (vibroseis point 29 on Figure

Table 1. Apparent vertical offset, in feet, at various depths along the westernmost Pond fault (LADWP, 1974).

Depth	Apparent offset
250	35
875	50
1,760	100
3,600	250

2). Offsets along the three easterly breaks appear too small to be measured at depths of less than 1500 feet (they do not appear to offset younger strata).

LADWP also concluded, based on Jennings (1975) and their interpretation of the subsurface data (principally vibroseis data), that the Pond fault was an extension of the Poso Creek fault (see Figures 1 and 2).

This investigator is somewhat bothered by the fact that the trends of the surface fault and the subsurface faults do not coincide and are only locally subparallel. This difficulty was not mentioned by LADWP. The possibility exists that although the surface fault may be related to the subsurface fault that has been postulated based on subsurface and geophysical data, the historic fault movement might be solely the result of subsidence due to groundwater withdrawal and not to tectonic forces.

Lofgren and Klausing (1969) and Poland and others (1975) have documented widespread subsidence in the Tulare-Wasco area (Figure 4). The fact that the displacement on the steeply dipping Pond fault appears to be primarily dip-slip (strike-slip evidence has not been reported) and that the groundwater table has been drastically lowered near Pond suggests that subsidence should be considered as a driving mechanism. Ireland and others (1982) indicate that the groundwater aquifer was being compacted at depths equal to those from which water was being produced. They based their conclusions on their observations of numerous wells in the San Joaquin Valley, including one located about 8 miles south of Pond. In the latter, they documented that subsidence was occurring at depths of 2200 feet below the surface.

Ireland and others (1982) also indicate that subsidence rates decreased in selected areas when large quantities of water were imported and pumping of ground water declined. Prior to the completion of the Friant-Kern Canal, the groundwater table had fallen substantially in the area around the agricultural towns resulting in the subsidence pattern shown in Figure 4 (greater subsidence near residential communities). The Friant-Kern Canal brought water to these communities, resulting in less water being pumped from the subsurface in the areas near the canal. In turn, this resulted in an increase in elevation of the water table in these same areas. During the drought of 1976-77, groundwater production increased substantially resulting in subsidence during this second cycle of water table decline typical of those observed during the initial cycle.

Comparison of the elevations of the water table in 1920 with those in 1959 (see Figure 5) reveals that the surface fault near Pond lies on a "water decline gradient". Perhaps this indicates that the subsurface Pond fault acts as a water barrier south of the Kern-Tulare County line where the water table southwest of the fault has declined much more than the water table to the northeast. This relationship appears reversed north of the county line. Therefore, if the continuing withdrawal of groundwater has resulted in surface displacement on the Pond fault (due to differing rates of subsidence on either side), then surface faulting hypothetically should neither continue northward nor southward without radically changing strike. If, however, the fault existed as a surface feature prior to the completion of the Friant-Kern Canal, then it may extend beyond into the adjacent areas.

INTERPRETATION OF AERIAL PHOTOGRAPHS

U.S.D.A. (1952) aerial photographs of the study area were examined stereoscopically to determine whether any features indicative of recent fault movement existed on or near the reported rupture zone. The area appears quite flat and lacks topographic features indicative of recent fault movement. Numerous tonal lineaments are visible on the photos (Figure 6). The clearest of these lineaments are obviously caused by alluvial processes (stream channels, etc.). Other lineaments appear to be related to agricultural activities or are otherwise caused by man. Many of the lineaments are vague or subtle.

A rather vague tonal lineament approximately coincides with the north-south trending segments of the rupture zone. This lineament can be traced discontinuously from a point about 1000 feet south of Elmo Highway to near the intersection of Shafter Road and Lytle Avenue. Just north of Elmo Highway this lineament is crossed by another, northwesterly trending lineament (probably a stream channel) which appears much better defined.

Because of the overwhelming number of tonal lineaments observed in the vicinity of the study area (not all of which are plotted on Figure 6), this investigator believes that interpretation of aerial photographs is of limited value in this instance. Certainly, the lineaments plotted on Figure 6 cannot be seriously considered as evidence in support of or against the existence of an active fault.

FIELD OBSERVATIONS

In early January 1983, an attempt was made to verify the evidence of surface faulting cited by LADWP (1974). At Peterson Road (Figure 6), this investigator found a few cracks in the pavement associated with a slight sag about 1" deep and 1' to 2' wide. This sag and cracks lie at the base of a 26" high ramp or scarp, which is about 50' to 75' wide. The field to the south has been dead-leveled. To the north a much narrower scarp can be discerned crossing a farm equipment storage area.

On Lytle Avenue, an 8' wide zone of cracked pavement within which a 1" to 2" high, sharp, southwesterly facing scarp in the pavement was observed. This sharp scarp lies on the southwestern side of the crack zone, which trends N. 32° W. A broad sag in the pavement, subparallel to the zone of cracking, is located about 50' to the south. This sag is about 2' deep and 100' wide.

On Elmo Highway, a north-south trending zone of rhombohedral cracks was observed on the eastern margin of a broad (75' wide), west-facing scarp in the pavement. About 8" of relief was apparent across this scarp. Fields on either side have been modified (agricultural activities).

The downdrop in Pond Road, reported by LADWP was not apparent. According to Mr. George Ansolabhre (Contract Officer for the County Road Department; oral communication, March 1983), Pond Road was last regraded and repaved in early 1980. Thus, any scarps or cracks in the old pavement would most likely have been obliterated at that time. Also, the fact that the county routinely regrades roads before repaving appears to account for the width of the scarp or ramp on Peterson Road and Elmo Highway.

Neither Benner Avenue nor Casey Avenue exhibited any signs of scarps or zones of cracking. A few dips were noted in the pavement of Benner Avenue south of the school, but if these dips reflect recent faulting, then the fault is not well defined at this location.

Roads to the south (Sherwood and Blankenship) were also checked, as were Wasco-Pond Road, Schuster Road, Mettler Road, State Highway 43, and Melcher Avenue. No evidence of recent faulting was observed along these roadways.

SEISMICITY

Real and others (1978) report no epicenters in the area studied herein (they show only earthquakes larger than magnitude 4.0). LADWP (1974) show six small (M 3.0-3.9) earthquake epicenters located within 6 miles of the Pond fault (Figure 7). This apparent zone of seismicity is centered about 4 miles south of and subparallel to the subsurface fault zone identified as the Pond-Poso Creek fault by LADWP. Although the surface projection of the subsurface fault zone lies in the "circle of horizontal location uncertainty," as calculated by LADWP, of only three of these epicenters, the pattern of epicenters appears consistent with the postulated southwesterly dip of the fault. The zone of surface faulting lies in the "circle of horizontal location uncertainty" of only one of these epicenters. These data suggest that the Pond fault might be seismically active, but are not conclusive.

CONCLUSIONS

Based on the field data and the LADWP (1974) report, it appears that the Pond fault has been the site of historic surface rupture and locally is sufficiently well defined to warrant zoning. Subsidence due to water withdrawal has been documented in the area (Lofgren and Klausing, 1969; Poland

and others, 1975; and, Ireland and others, 1982) and may be the cause of the most recent episode of fault displacement. The repeated rupturing of a pipeline along Elmo Highway (LADWP, 1974), as well as the distorted pavement identified by LADWP in 1974 and this investigator in 1983, suggest that movement on the Pond fault has been recurrent and is probably continuing.

LADWP suggested that the surface displacement is related to a fault identified by subsurface information. Based on this subsurface data, it appears that the subsurface Pond fault consists of a broad zone of faults that apparently has had a long history of movement (see Table 1). This investigator is not entirely convinced that the historic surface faulting is tectonically caused. However, the historic faulting may be indirectly related to the pre-existing faults if one or more of the pre-existing faults act as a water barrier (which is apparently the case). Differing rates of decline in the water table on either side of the subsurface fault could be the entire cause of the historic fault movement. No evidence of historic rupture on the Pond fault beyond the area identified on Figure 2 has been found, and the subsurface fault does not appear well-enough defined to warrant zoning.

RECOMMENDATIONS

The Pond fault should be zoned approximately as shown on Figure 8. The principal references cited should be the LADWP (1974) report and this FER. No other strands of the postulated Pond-Poso Creek fault zone should be zoned at this time.

I concur with the recommendations.
EWH
4/13/83

Theodore C. Smith

THEODORE C. SMITH
Associate Geologist
R.G. #3445, C.E.G. #1029
April 12, 1983

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Ireland, R.L., Poland, J.F., and Riley, F.S., 1982, Land subsidence in the San Joaquin Valley, California as of 1980: U.S. Geological Survey Open-File Report 82-370, 129 p.

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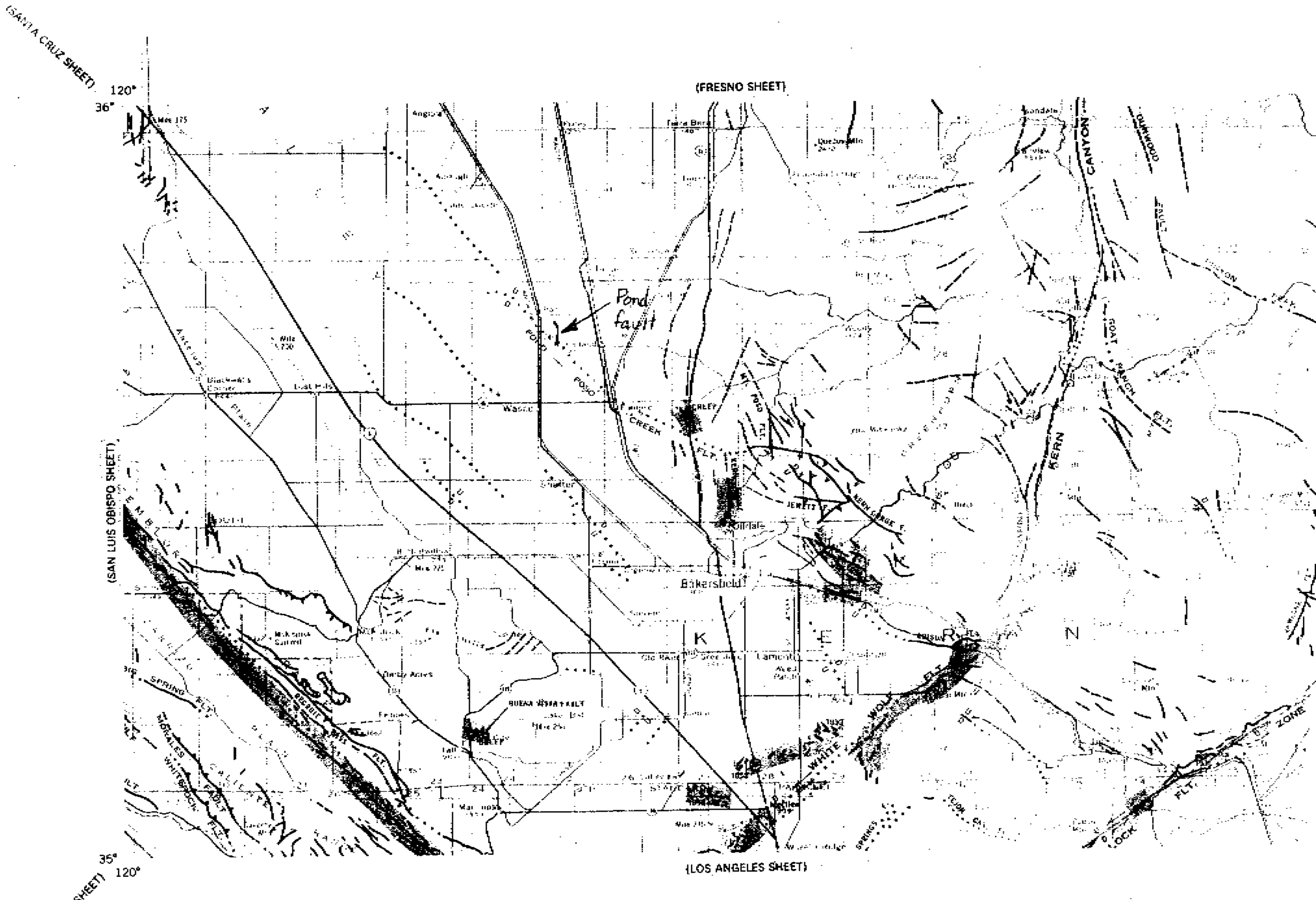

Figure 1. Location of the Pond fault (after Jennings, 1975).

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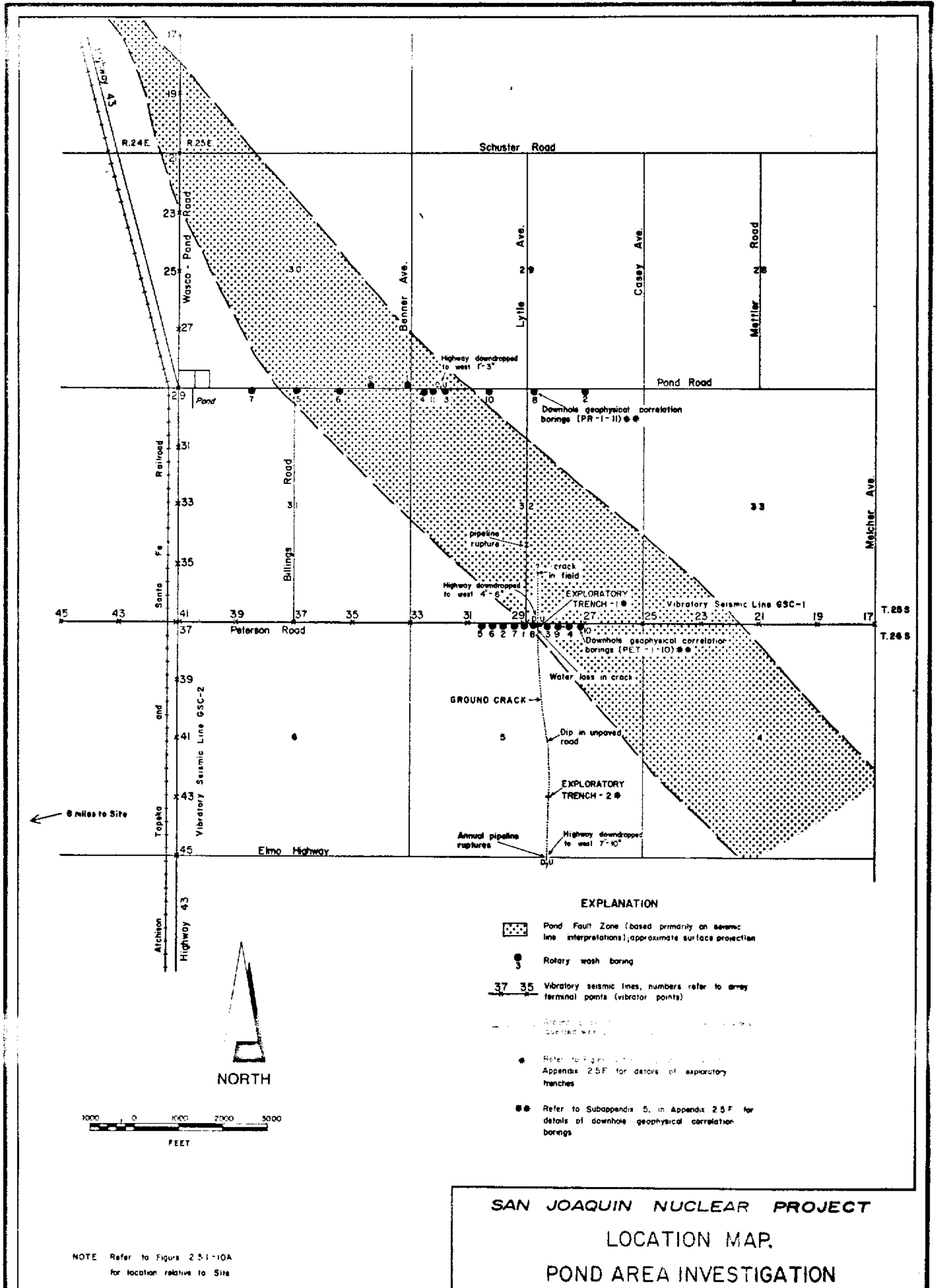

Figure 2. Map of the Pond fault (from LADWP, 1974).

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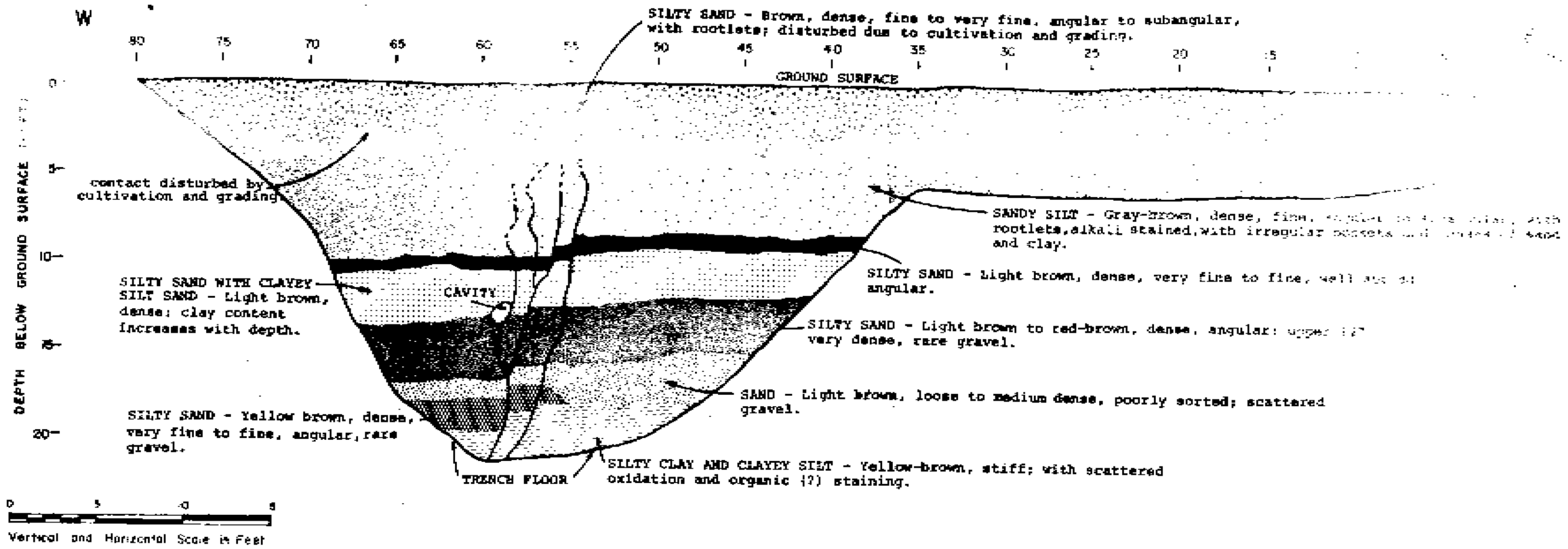
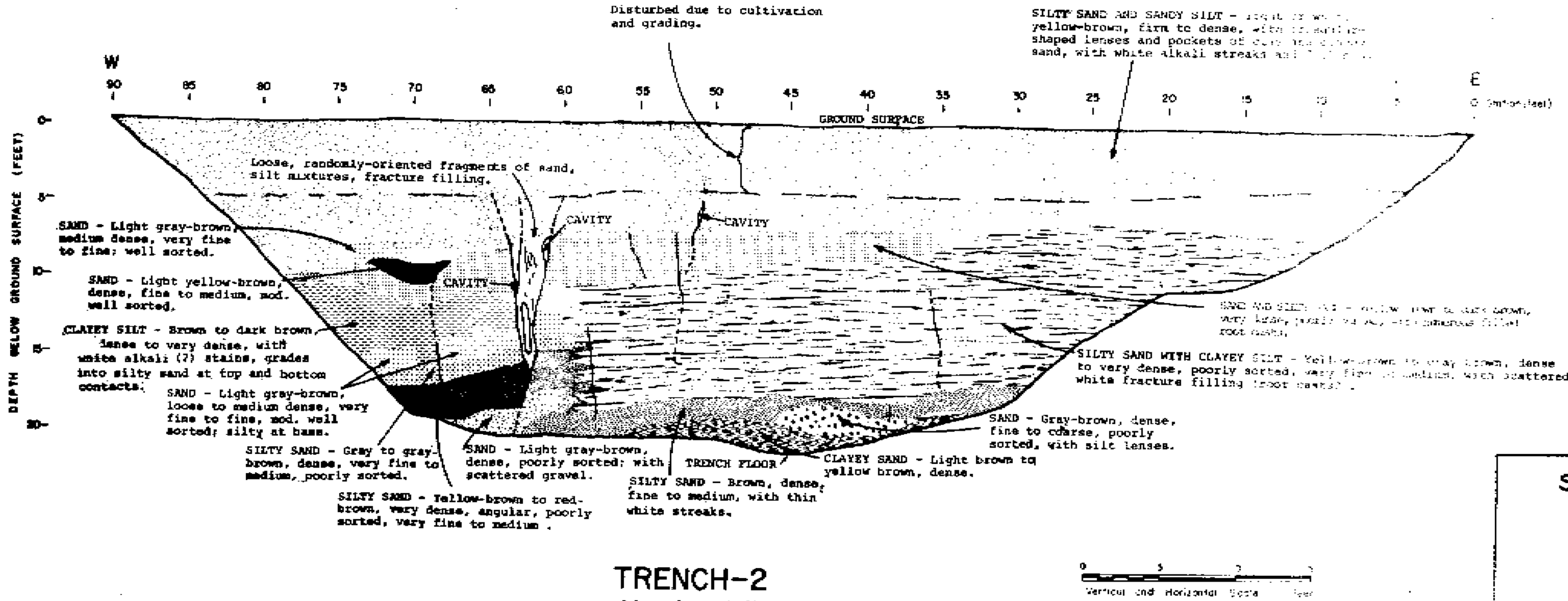


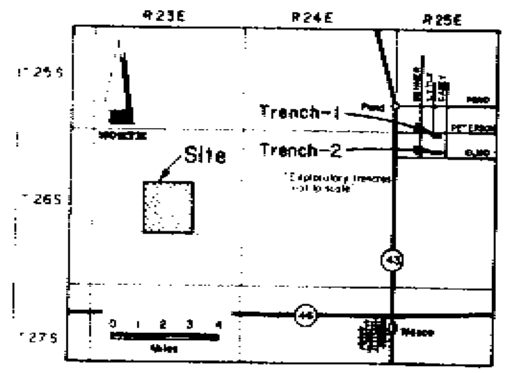
TRENCH-1
North Wall



TRENCH-2
North Wall

EXPLANATION

TRENCH LOCATION MAP, POND AREA



NOTE: i) For extent of crack in plan view, see Figure 2.5.1-10c
ii) Patterned soil contacts not well defined.

SAN JOAQUIN NUCLEAR PROJECT

POND AREA INVESTIGATION, TRENCH PROFILES

Figure 3. Logs of the trenches across the Pond fault (from LADWP, 1974).

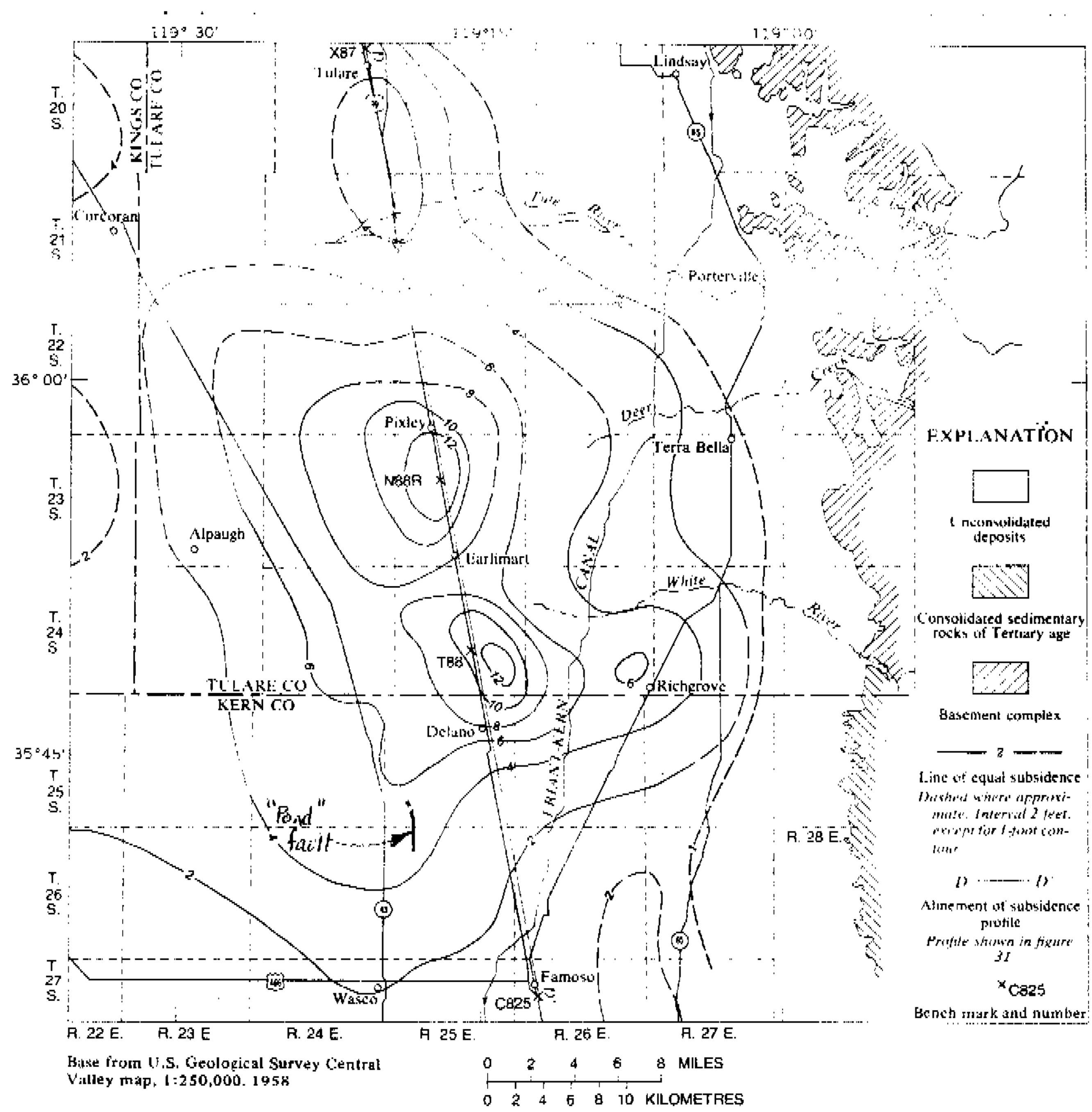


Figure 4. Land subsidence, 1926-1970, Tulare-Wasco area (from Poland and others, 1975). Approximate location of Pond fault indicated in red.

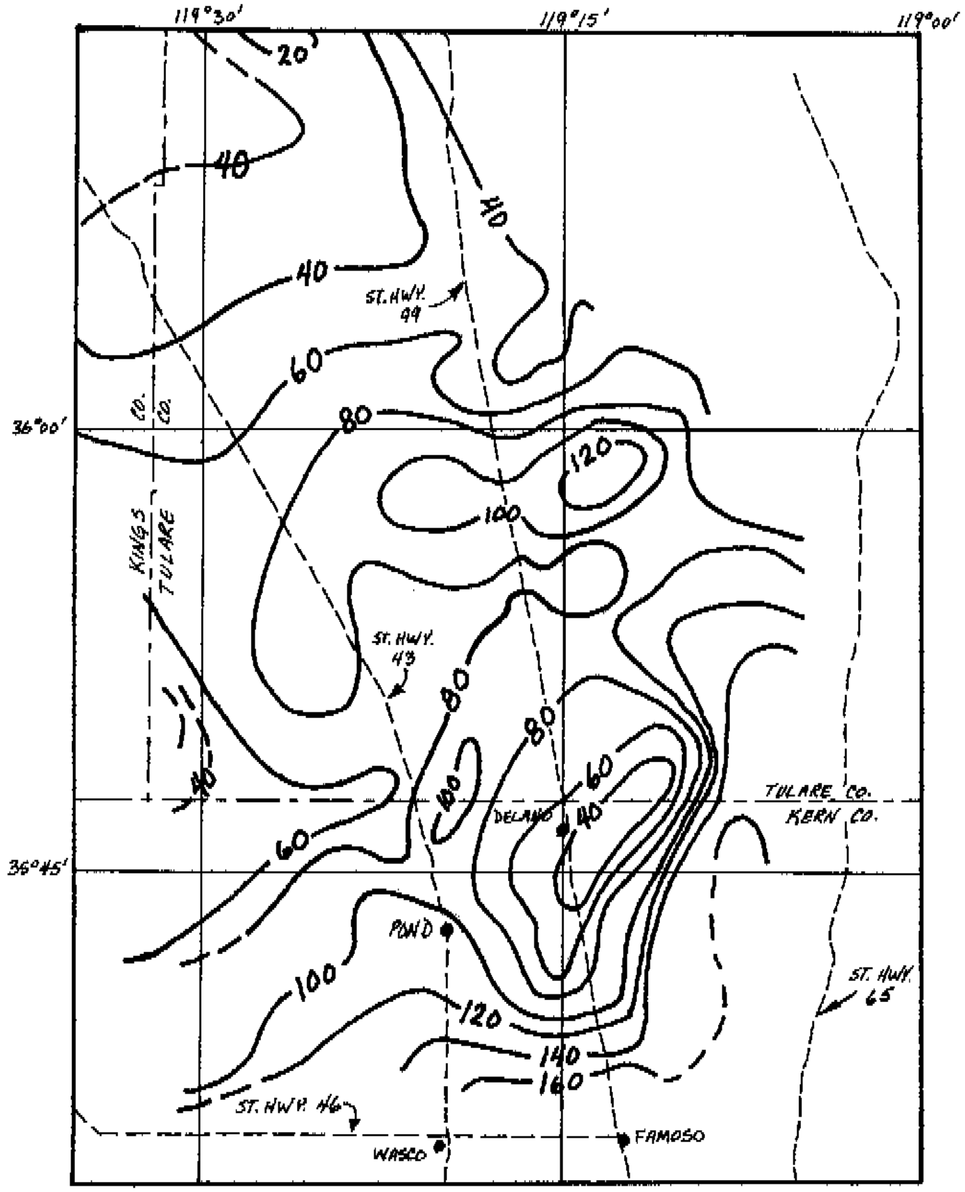
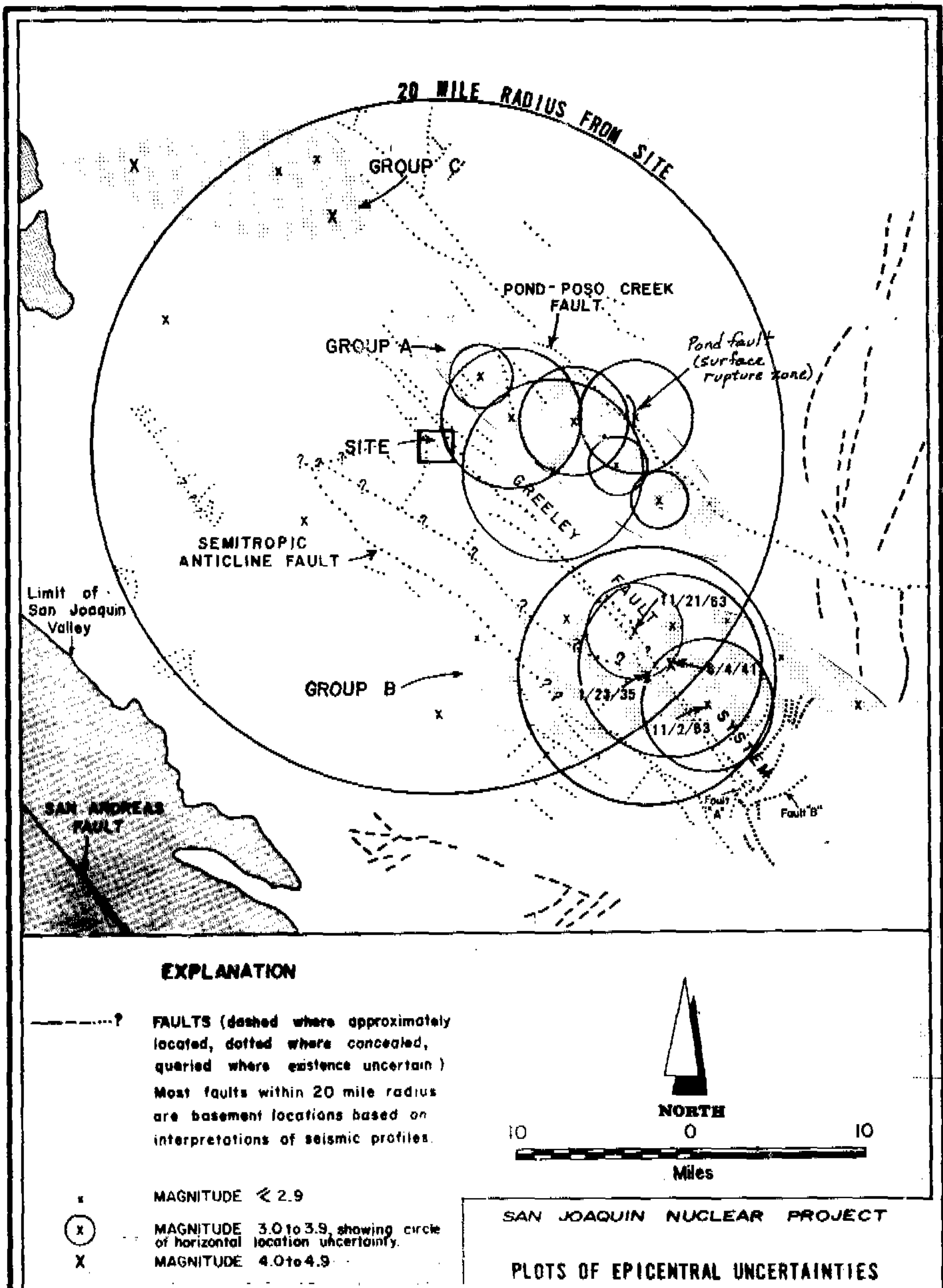


Figure 5. Map showing the decline in the water table, 1920-1959. Contour interval 20 feet. Based on Figures 23 and 28 of Lofgren and Klausing (1969).



FER-144. Figure 7. Map of earthquake epicenters in the vicinity of the Pond fault (after LADWP, 1974).

United States Department of the Interior

GEOLOGICAL SURVEY

OFFICE OF EARTHQUAKES, VOLCANOES, AND ENGINEERING
Branch of Engineering Seismology and Geology
345 Middlefield Road, MS 977
Menlo Park, CA 94025

September 17, 1985

Mr. Robert H. Sydnor
California Division of Mines and Geology
380 Civic Center, Suite 100
Pleasant Hill, California 94523-1997

RE: Pond fault, Northern Kern County

Dear Bob:

Thank you for the copy of the Fault Evaluation Report, FER-144, on the Pond fault. First, the good news. The report suggests that ground-water withdrawal is the cause of the historical offset on the segment of the fault south of Pond. The bad news is that this relation was much more thoroughly documented and published in Water Resources Research (v. 16, no. 6, pp. 1065-1070) in 1980. A copy is enclosed. I had the good fortune to be monitoring the fault during and after the California drought in 1977-1978, and it moved everytime water levels declined. The fresh ground cracking was quite obvious during these periods of offset, and I could have supplemented Ted's field observations with a few that I made at the time.

It is disconcerting that the draft came to the USGS for review and there was no comment. Obviously, we should have commented. I do not know what our review procedures are, but I will bring this example to the attention of the Assistant Chief Geologist for the Western Region. Fortunately the practical impact of this oversight is probably zilch since Pond was showing no signs of urban growth during my last visit. My interest was stirred by the now defunct South San Joaquin Nuclear Reactor, and I suppose it is possible that it may raise its head again some day.

Incidentally, the USGS has a bench-mark array buried on the south side of Peterson Road. It was last reoccupied in the Spring of 1982. As of then, the fault had not moved since the drought-related offset.

Best regards,

Tom

Thomas L. Holzer

Enclosure

cc: J. R. Filson
T. C. Hanks
E. W. Hart
C. A. Hodges
T. C. Smith

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SAN FRANCISCO D.O.

WATER RESOURCES RESEARCH, VOL. 16, NO. 6, PAGES 1065–1070, DECEMBER 1980

Faulting Caused by Groundwater Level Declines, San Joaquin Valley, California

THOMAS L. HOLZER

U.S. Geological Survey, Menlo Park, California 94025

Approximately 230 mm of aseismic vertical offset of the land surface across the Pond-Poso Creek fault in the San Joaquin Valley, California, probably is related to groundwater withdrawal for crop irrigation. The scarp is approximately 3.4 km long and occurs in an area where the land subsided more than 1.5 m from 1926 to 1970. Modern faulting postdates the beginning of water level declines and associated subsidence. Movement detected by precise leveling surveys from February 1977 to March 1979 was seasonal, occurring during periods of water level decline. Fault offset was greater in the year with the lower seasonal low water level. The modern movement probably is caused by localized differential compaction induced by differential water level declines across the preexisting fault.

INTRODUCTION

Surface faulting is associated with land subsidence caused by groundwater withdrawal in Arizona [*Holzer et al.*, 1979], California [*Clark et al.*, 1978; *Rogers*, 1967], Texas [*Kreitler*, 1977; *Van Siclen*, 1967], and Mexico (G. Figueron Vega, oral communication, 1977). Although the relation between many of these surface faults and groundwater withdrawal is ambiguous because faulting caused by natural geologic processes cannot be excluded, some of this faulting is probably caused by the groundwater withdrawal. Arguments for a relation for individual faults include seasonal fault movement or correlation of fault movement with fluctuations of groundwater level [*Holzer et al.*, 1979; *Nason et al.*, 1974; *Reid*, 1973], temporal and areal association of modern surface faulting with groundwater withdrawal [*Clark et al.*, 1978; *Holzer et al.*, 1979; *Lockwood*, 1954], and restriction of modern subsurface fault offset to within the aquifer [*Holzer et al.*, 1979]. Because several of these surface faults have been demonstrated to connect to preexisting faults [*Clark et al.*, 1978; *Holzer*, 1978; *Van Siclen*, 1967; *Woodward-Lundgren and Associates*, 1974], man-induced declines of groundwater level may be capable of causing renewed movement on preexisting faults.

The Pond-Poso Creek fault is a preexisting fault in the southern San Joaquin Valley, California, along which modern aseismic surface faulting is occurring. Modern faulting is restricted to an area of land subsidence caused by water level declines and postdates the beginning of declines. Although modern movement has been attributed to tectonism, *Holzer* [1977] suggested that the movement might be related to groundwater withdrawal. In this report, measurements of fault movement and water levels are described that further support a relation between modern faulting and groundwater withdrawal. From February 1977 to March 1979 the fault moved at monitored sites only during periods of water level decline. During periods of water level recovery, fault movement ceased. In addition, annual fault offset was greater in the year with the lower seasonal low water level. Water level data and the estimated compressibility of the aquifer system suggest that the modern faulting was caused by differential compaction across a partial groundwater barrier associated with the Pond-Poso Creek fault zone.

Paper number 80W0998.

POND-POSO CREEK FAULT

The Pond-Poso Creek fault is a preexisting geologic fault that trends northwesterly for approximately 60 km from the eastern margin of the south San Joaquin Valley to near the center of the valley [*Los Angeles Department of Water and Power*, 1974]. The fault is exposed at the surface along its southeastern end, but elsewhere, except for the 3.4-km long scarp shown on Figure 1, is concealed by alluvium. Seismic reflection data collected in the vicinity of the active surface trace (Figure 1) indicate the Pond-Poso Creek fault in that area is an approximately 1-km-wide zone of four subparallel normal faults that trend northwesterly and dip from 50° to 70° to the southwest [*Los Angeles Department of Water and Power*, 1974]. Offset is greatest on the westernmost fault and decreases surfaceward. At a depth of 267 m, near the base of most irrigation wells in the study area, vertical offset across the westernmost fault is interpreted to be 15.2 m. Borehole data indicate the westernmost fault has caused approximately 11 m of offset of a distinctive clayey zone, identified as the Corcoran Clay Member of the Tulare Formation, at a depth of approximately 76 m [*Los Angeles Department of Water and Power*, 1974]. Total cumulative vertical offset of the Corcoran across the fault zone is estimated to be 24 m. The average rate of fault offset on the westernmost fault, since deposition of the Corcoran is less than 0.018 mm/yr based on an age of the clay of more than 600,000 years [*Miller et al.*, 1971]. Although the Pond-Poso Creek fault has been considered to be a capable fault, no historic earthquakes with magnitude greater than 4 can be associated with the fault [*Los Angeles Department of Water and Power*, 1974].

The modern surface faulting occurs on the northern part of the Pond-Poso Creek fault. Because the scarp formed by modern faulting (Figure 2) is continuously modified in cultivated areas between roads, the scarp is preserved only where it intersects paved roads and in a small uncultivated area immediately north of Peterson Road. Connection of these scarps suggests that a more than 3.4-km-long segment of the fault is active. Because the paved roads have been periodically regraded and resurfaced, total historic or modern offset of the land surface can be only estimated. An upper limit to historic offset as of 1974, however, was established by trenching of the fault between Elmo Highway and Peterson Road (Figure 2). At a depth of 3 m from the land surface, approximately 230 mm of vertical offset was observed [*Los Angeles Department of*

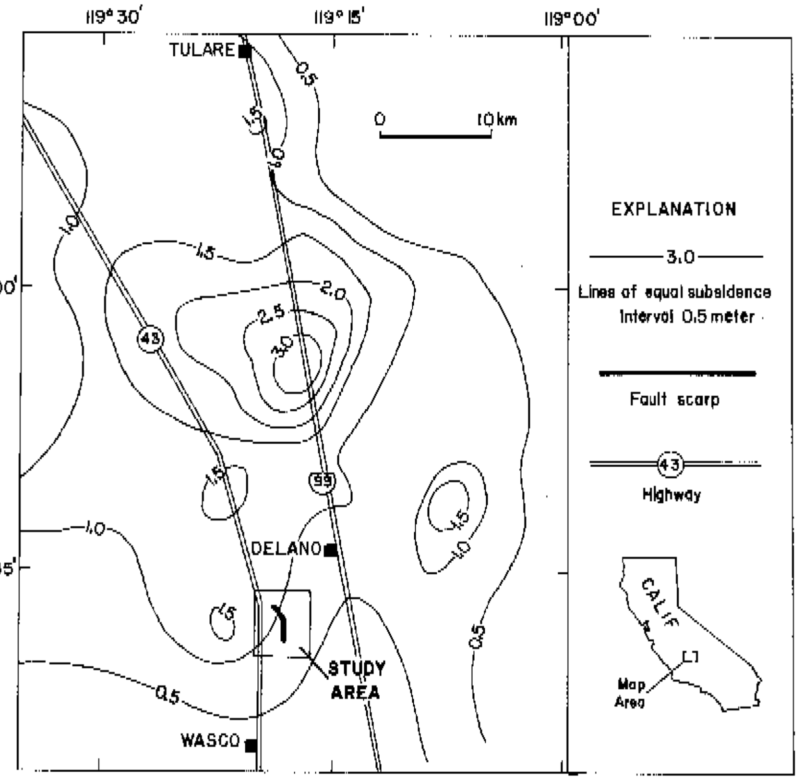

Fig. 1. Map of Tulare-Wasco, California, subsiding area, modern fault scarp formed by the Pond-Poso Creek fault, and study area. Land subsidence, 1948-1970, modified from *Poland et al.* [1975].

Water and Power, 1974]. This amount is compatible with estimates of total historic offset based on the regraded road surfaces. The date of the beginning of surface faulting can be established only approximately. A profile of the land surface in the uncultivated area north of Peterson Road, which was regraded in 1971 and left undisturbed, indicated 136 mm of fault offset as of September 1978. Based on the amount of offset observed in the trench and the average rate of fault offset determined from the height of the scarp at the creepmeter site, faulting is estimated to have begun in or after the late 1950's. This date is supported by the observation of county highway maintenance personnel that fault offset of paved roads was not noticed until sometime between 1956 and 1966 (H. Silva, oral communication, 1976) and by reports of local farmers that surface effects from faulting in cultivated areas were first noticed in the 1950's.

HYDROLOGY AND LAND SUBSIDENCE

The freshwater bearing zone in the study area is divided into a confined and an unconfined aquifer, and the Corcoran Clay is the principal confining bed between the two [*Davis et al.*, 1959]. The freshwater bearing zone is underlain by saline water at a depth of approximately 580 m [*Page*, 1973]. Groundwater production is restricted to above the interface between the freshwater and saltwater; most irrigation wells in the study area are less than 320 m deep. The confined aquifer is extensively developed for crop irrigation. The study area, however, also relies heavily on imports of surface water from the Friant-Kern Canal. Both the water table in the unconfined aquifer and the potentiometric surface of the confined aquifer have been significantly modified by groundwater withdrawals. Water surfaces in both aquifers in the study area slope westward toward closed water level depressions west of the study area [*California Department of Water Resources*, 1977*b*]. Some of the history of groundwater development in the study area is reflected in the hydrograph of well 25/25-28R1 (Figure 3), which is perforated in the confined aquifer. The early history of groundwater development is poorly documented, but *Mendenhall et al.* [1916] reported that wells were free flowing in 1905. By the early 1930's, significant water level declines had occurred (Figure 3). After World War II the cultivation of new acreage requiring additional groundwater withdrawal accelerated the water level declines [*Lofgren and Klausing*, 1969]. With completion of the Friant-Kern Canal in 1951, groundwater pumpage and associated water level declines decreased relative to the postwar period. The hydrograph indicates that the long-term decline of water levels was not completely arrested in the study area by the surface water imports. The hydrograph of 25/25-28R1 also reveals that water levels in the confined aquifer fluctuate annually approximately 20 m, reflecting a strong seasonal demand for groundwater.

The study area lies within the Tulare-Wasco subsidence area, which is part of the extensive subsiding region in the San Joaquin Valley [*Poland et al.*, 1975]. Land subsidence caused by declining groundwater levels has been documented in the study area by *Lofgren and Klausing* [1969]. Based on maps of subsidence [*Lofgren and Klausing*, 1969; *Poland et al.*, 1975], approximately 2 m of subsidence occurred at the fault from 1926 to 1970. Slightly more than half of this subsidence is estimated to have occurred from 1948 to 1970 (Figure 1). Because of the large seasonal water level fluctuation in the Tulare-Wasco area, compaction causing the land subsidence is predominantly seasonal; most of the annual compaction occurs

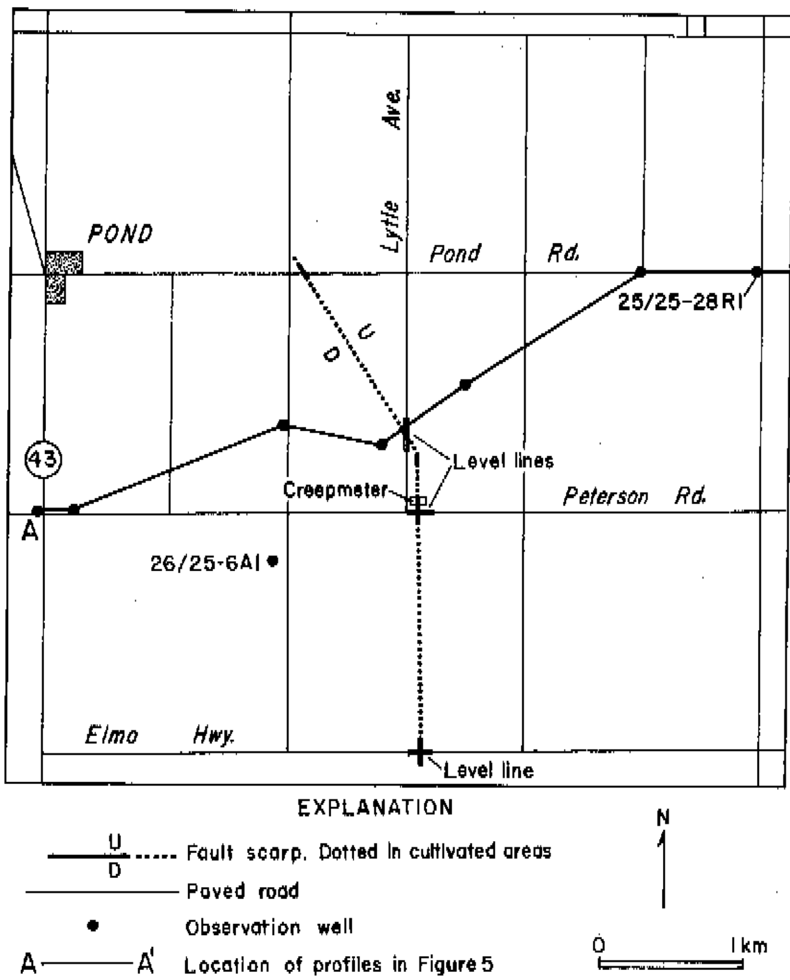

Fig. 2. Map of study area with modern fault scarp, fault monitoring sites, and wells referenced in text. See Figure 1 for location of study area.

during the summer period of groundwater withdrawal [*Lofgren and Klausing,* 1969].

FAULT MONITORING

Level lines to monitor fault movement were established in 1977 on three paved roads intersected by the modern fault scarp (Figure 2). Bench marks consisted of 64-mm-long P-K nails driven flush with the pavement along the center line of the roadways. Bench marks were spaced symmetrically about the surface scarp from 1.5 to 46 m from the scarp. All leveling before March 1978 was performed with a Jena Dahlta 010A theodolite and Philadelphia rod with a micrometer. Measurements were reproducible to 1 mm with this system. Leveling after February 1978 was performed with a Zeiss Ni-1 automatic level and invar survey rods, a system designed for precise geodetic leveling. In September 1977 a tiltbeam or creepmeter with a nominal sensitivity of 0.097 mm/m [*Nason,* 1971] was established across the fault 67 m north of Peterson Road (Figure 2). The creepmeter was read manually. Because the ends of the tiltbeam were 1.7 m apart, the tiltbeam presumably measured only vertical offset across the fault.

Results from monitoring are summarized in Figures 4*a* and 4*b*. Only measurements of differential vertical displacement of the bench marks closest to and on either side of the fault are shown because results from level lines indicated that adjacent sides of the fault moved uniformly to a distance from the fault covered by the level lines. All of the records are dominated by fault movement during the summer months. The record at Elmo Highway is the longest and indicates 17.5 mm of fault offset, downthrown to the west, from May to September 1977 (Figure 4*a*). An additional 2 mm of fault offset may have occurred from September to November. From November 1977 to March 1979 no fault offset was detected. At Peterson Road,

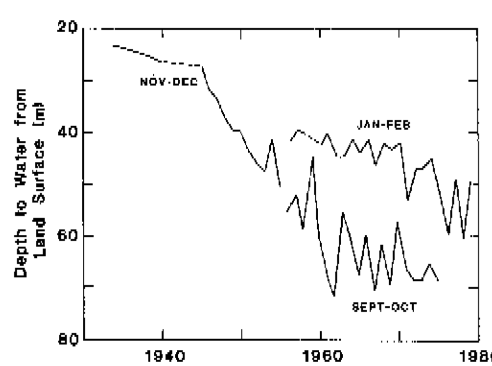

Fig. 3. Graph of water levels for different months in irrigation well 25/25-28R1 (see Figure 2 for location). January–February and September–October measurements are approximately the highest and lowest annual water levels, respectively.

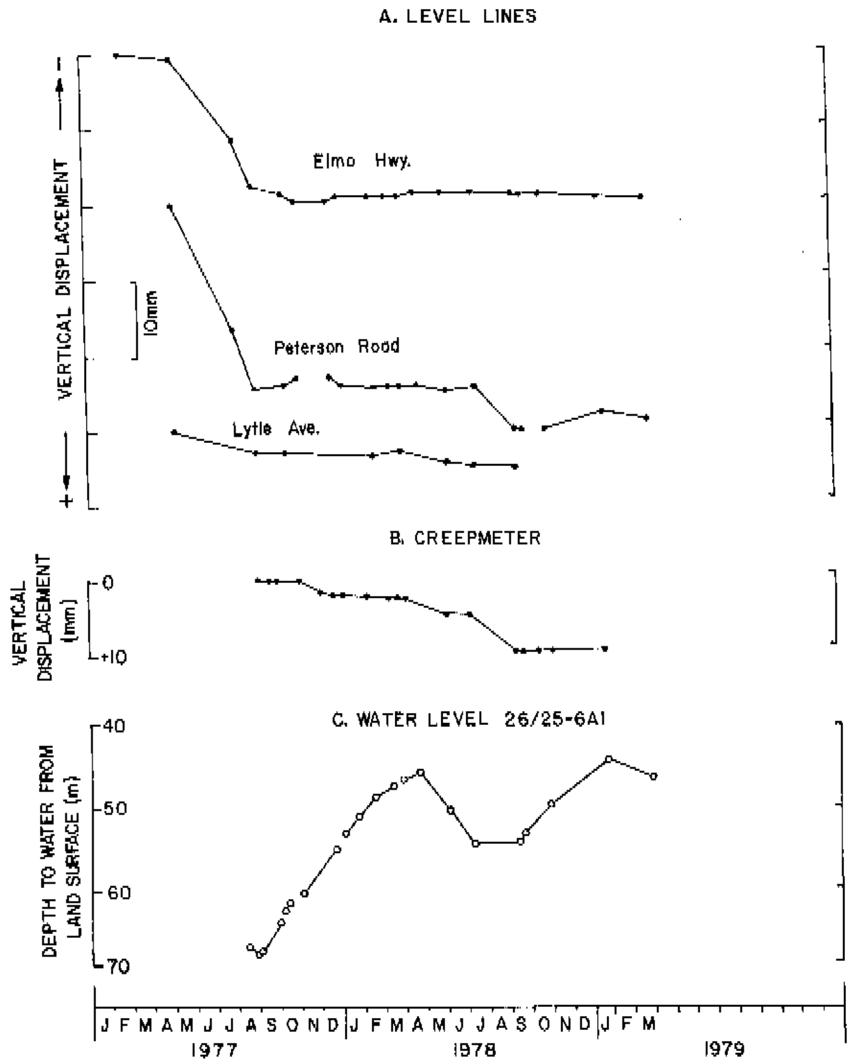

Fig. 4. Differential vertical displacement of bench marks ±1.5 m from fault scarp at paved roads, February 1977 to March 1979 (increase in height of fault scarp is positive). (*b*) Creepmeter record, September 1977 to January 1979 (increase of height of fault scarp is positive). (*c*) Depth to water in well 26/25-6A1, August 1977 to March 1979.

monitoring began in May 1977. During the period from May to September 1977, contemporaneous with the surveys at Elmo Highway, 24.5 mm of fault offset, downthrown to the west, was measured (Figure 4*a*). From September to November, 1.5 mm of fault offset in an opposite sense to that of the summer may have occurred. The bench marks were subsequently destroyed and were reset in December 1977. No renewed offset was detected until the period from July to September 1978 when 5.5 mm of offset was measured. Taping between the bench mark pair across the fault at Peterson Road, accurate to 1 mm, detected no horizontal movement associated with the faulting in 1978. Measurements 8 days apart in September indicate that fault movement had halted prior to the date of the first measurement in September. Bench marks again were destroyed and were not reset until the end of October. Fault offset at Lytle Avenue from May 1977 to September 1978 was barely detectable. Approximately 3 mm of offset, downthrown to the south, occurred from May to September 1977 (Figure 4*a*). Results from the creepmeter (Figure 4*b*), 67 m north of Peterson Road, are in approximate agreement with the results from the monitoring at Peterson Road. The offset of 1.8 mm measured by the creepmeter in November-December 1977 occurred during the recordless period at Peterson Road and hence was not confirmed by independent measurements. The piers of the creepmeter consisted of steel rods driven to only 1.4 m and supported laterally to a depth of only 1.1 m by concrete. Hence the November-December movement detected by the creepmeter may have been a consequence of settlements caused by the nature of the installation itself. The offset of 1.9 mm detected at the creepmeter from April to May 1978 was not confirmed by measurements

TABLE 1. Annual Surface Water Deliveries to Study Area From Friant-Kern Canal

Year	Delivery
1970	18.50
1971	16.74
1972	14.61
1973	15.24
1974	17.15
1975	17.56
1976	6.88
1977	3.65
1978	12.62

In 10^6 m^3.

at Peterson Road which casts suspicion on its origin as well. Offset of 5.0 mm from June to September agrees with the measurement at Peterson Road. The creepmeter was disabled after January 1979.

WATER LEVEL MONITORING

Water levels in both domestic and irrigation wells were measured in the study area. In addition, the water level in an abandoned irrigation well was measured during each geodetic survey. Irrigation wells in the study area in general are perforated in the confined aquifer. Domestic wells, in general, are completed in the water table aquifer.

The seasonal variation of water levels was monitored by repeated measurements in an abandoned irrigation well, 26/25-6A1, approximately 1 km west of the fault scarp (Figure 2). Records on file with the California Department of Water Resources report that the well is perforated from 61 to 213 m. In addition to showing a large seasonal fluctuation of water level the hydrograph (Figure 4*c*) also illustrates the effect on water levels from a drought in the mid-1970's. In 1976 and 1977, imports of surface water via the Friant-Kern Canal were greatly curtailed by the drought (Table 1) and the deficiency was made up by pumping groundwater. In 1978 the return of surface water supplies to their predrought quantities reduced groundwater withdrawals. The slightly smaller delivery of surface water in 1978 relative to pre-1976 deliveries (Table 1) was caused by abnormal spring and fall rainfall in 1978 that reduced the demand for surface water. In response to decreased groundwater production following the drought the lowest water level measured in 1978 was 14.0 m higher than the lowest water level measured in 1977.

Water levels were measured in 26 accessible wells in January 1978 and 21 wells in July 1978. Less complete surveys were conducted in September 1978 and January 1979. With a few exceptions, when measurements were separated according to the principal aquifer tapped by the well, water levels were consistent for each aquifer. Water levels in wells reported to be perforated in both aquifers, in general, were consistent with water levels in wells reported to be perforated only in the confined aquifer. In January 1978 the difference between water levels in shallow and deep wells, i.e., wells tapping the unconfined and confined aquifers, respectively, was approximately 35 m. The potentiometric surface for the confined aquifer, shown in an east-west profile in Figure 5, sloped in a westerly direction. During the summer of 1978, water levels in deep wells on the west side of the fault scarp declined approximately 12 m as contrasted with declines of 3 m or less on the eastern side of the fault scarp. This response, in part, was caused by the distribution of pumping during the summer. The area west of Highway 43 (see Figure 2), although under cultivation, received negligible surface water and hence was largely dependent on groundwater. Pumping in 1978 east of Highway 43 in the study area was minor. Despite the large declines measured in the deep wells, water levels in shallow wells changed less than 1 m from January to July.

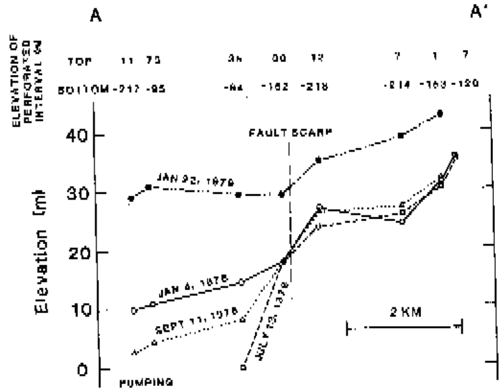

Fig. 5. Profiles of water levels in irrigation wells, January 1978 to January 1979. Elevation (in meters) of top and bottom of reported perforated interval in each well is shown. Top of confined aquifer is approximately at mean sea level. See Figure 2 for location of profiles.

DISCUSSION

Movement of the Pond-Poso Creek fault in 1977 and 1978 only during the summer period of groundwater withdrawal suggests a relation between modern faulting and declines of groundwater level. Comparison of the records of fault movement with the hydrograph of monitor well 26/25-6A1 further supports such a relation (Figure 4). In both 1977 and 1978, fault movement essentially stopped during periods of water level recovery. The greater amount of fault movement in 1977 relative to 1978 also is consistent with the water level observed in the monitor well. The seasonal low water level was 14.0 m lower in 1977 than in 1978, indicating greater stressing of the system in 1977.

These observations, which suggest that the modern faulting is related to water level declines, do not by themselves indicate the specific mechanism of faulting. For example, a minor reduction of horizontal stress at a normal fault already near failure could trigger fault movement. Although this mechanism cannot be excluded, water level and aquifer compressibility data suggest that differential compaction localized across the Pond-Poso Creek fault is a more likely mechanism. A fault-controlled partial groundwater barrier is suggested by the 20-m difference of water levels across the fault zone observed in irrigation wells in July 1978 (Figure 5) and by matching to historical water levels, groundwater levels computed by a digital computer model of the confined aquifer system [*California Department of Water Resources*, 1977*a*]. In addition, a water level difference of 9.1 m localized across the modern scarp was reported in closely spaced, undeveloped, 152-m deep exploratory test holes drilled in 1974 [*Los Angeles Department of Water and Power*, 1974]. Based on an appropriate ratio of subsidence to water level decline of 0.03 [*Lofgren and Klausing*, 1969, Figure 69], a water level difference localized across the preexisting fault of only 7.8 m would be required to cause the 230 mm maximum possible historic fault offset as of 1974.

The record of fault movement on the Pond-Poso Creek fault and the presence of a preexisting fault inferred to be a partial groundwater barrier are similar to conditions reported by *Holzer* [1978] and *Holzer et al.* [1979] at the Picacho fault in southcentral Arizona, a fault on which modern movement was attributed to groundwater withdrawal. In those studies it also was concluded that observed seasonal movement was caused by localized seasonal differential water level declines across a preexisting fault. The record of fault movement on the Pond-Poso Creek fault also is similar to some of the records of movement on faults in the Houston, Texas, subsidence area. Some but not all of the movement on monitored faults there correlated with water level fluctuations [*Gabrysch and Holzer*, 1978; *Kreitler*, 1977; *Reid*, 1973]. Evidence for fault-controlled partial groundwater barriers there is inconclusive (see *Kreitler* [1977] and *Gabrysch and Holzer* [1978] for discussion of the evidence).

CONCLUSIONS

Modern offset of approximately 230 mm since the 1950's on the Pond-Poso Creek fault is temporally and areally correlated with man-induced water level declines. Fault movement from February 1977 to March 1979 was seasonal, occurring during annual periods of water level decline. In addition, fault offset was greater in the year with the lower seasonal low water level. Based on these observations, modern faulting probably is related to declines of groundwater level. Seasonal differential water level declines observed across the preexisting fault zone suggest that the fault is a partial groundwater barrier. A localized differential decline directly beneath the modern scarp is suggested by water levels measured in undeveloped test holes. If such localized declines have occurred, then localized differential compaction across the preexisting fault may be the cause of the modern fault movement.

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